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Advanced Telepresence Surgery System Development

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ABSTRACT

SRI International is currently developing a prototype remote telepresence surgery system, for the Advanced Research Projects Agency (ARPA), that will bring life-saving surgical care to wounded soldiers in the zone of combat. Remote surgery also has potentially important applications in civilian medicine. In addition, telepresence will find wide medical use in *local* surgery, in endoscopic, laparoscopic, and microsurgery applications. Key elements of the telepresence technology now being developed for ARPA, including the telepresence surgeon's workstation (TSW) and associated servo control systems, will have direct application to these areas of minimally invasive surgery. The TSW technology will also find use in surgical training, where it will provide an immersive visual and haptic interface for interaction with computer-based anatomical models. In this paper, we discuss our ongoing development of the MEDFAST telesurgery system, focusing on the TSW man-machine interface and its associated servo control electronics.

INTRODUCTION

SRI International is currently developing a prototype remote telepresence surgery system, for the Advanced Research Projects Agency (ARPA), that will bring life-saving surgical care to critically wounded soldiers in the combat zone (CZ). Using SRI's

telepresence technology, a surgeon located in a mobile army surgical hospital (MASH) unit or base hospital will carry out emergency surgical procedures on soldiers in an armored mobile surgical vehicle in the CZ. Dubbed the *Medical Emergency Forward Area Surgical Telepresence* (MEDFAST) system, this vehicle will contain a fully equipped telepresence operating theater, and a medic in the MEDFAST will assist the remote surgeon.

Remote telepresence surgery also has applications in civilian medicine, where it will enable specialists in regional medical centers to treat patients in outlying clinics. In addition, telepresence will most likely find wide medical use in *local* surgery—in endoscopic, laparoscopic, and microsurgery applications, and will play an important role in surgical training, providing an immersive visual and haptic interface to computer-based anatomical models.

In current practice, microsurgery involves delicate manipulation of small tissue structures viewed through a stereo microscope. While major reconstructive efforts such as reattachment of severed digits are routinely performed, these microsurgical procedures are often long and exhausting, with the surgeon spending many hours of concentrated work looking through microscope eyepieces, sitting in an awkward position [Franken et al., 1995]. In addition, human performance limitations preclude the extension of microsurgical techniques to new applications using higher magnification. The time to complete a task increases in proportion to the visual magnification required to complete it [Szabo, 1994]. Therefore, increases in magnification result in longer procedures, which increase patient risk and incur greater financial costs.

Similar limitations exist for laparoscopic surgery as currently practiced. It has largely replaced open surgery for relatively simple procedures such as cholecystectomy and hernia repair, and brings substantial benefits to the patient, including shorter hospital stay, faster recovery, and less cosmetic damage. However, with current instrumentation, laparoscopic procedures require more operating room time and are much more difficult for the surgeon than equivalent open procedures. As a result, relatively few surgeons will be able to progress from laparoscopic cholecystectomy to more complex procedures in the bowel and esophagus. The problem: laparoscopic surgery currently entails awkwardly maneuvering long instruments that are fulcrumed in the patient's abdominal wall (so that the motion of the tool tips is opposite to the motions of the surgeon's hands), while viewing the surgical field on a 2D video display located on a stand above the patient. This arrangement makes hand-eye coordination very difficult, and provides the surgeon with very little force feedback.

SRI's telepresence technology can overcome many of the limitations imposed by current minimally invasive surgery (MIS) instrumentation and methods. By enabling a great increase in the range and number of procedures that can be performed, telepresence will bring the benefits of MIS to many more patients.

In the case of microsurgery, telepresence systems will provide motion and visual scaling along with amplified force feedback that will allow surgeons to perform microsurgical procedures with the same speed, skill, and dexterity they achieve in full-scale open surgery. Similarly, for laparoscopic and other endoscopic procedures,

telepresence systems will provide an intuitive and effective interface for telepresence surgery that will greatly enhance surgeons' capabilities.

Key elements of the MEDFAST system we are now developing, including the telepresence surgeon's workstation (TSW) and associated servo electronics, will find direct use in these MIS telepresence systems and will play an important role in future MIS practice. In addition, the new TSW will be useful in surgical training, providing an excellent visual and haptic interface for interaction with computer-based anatomical models.

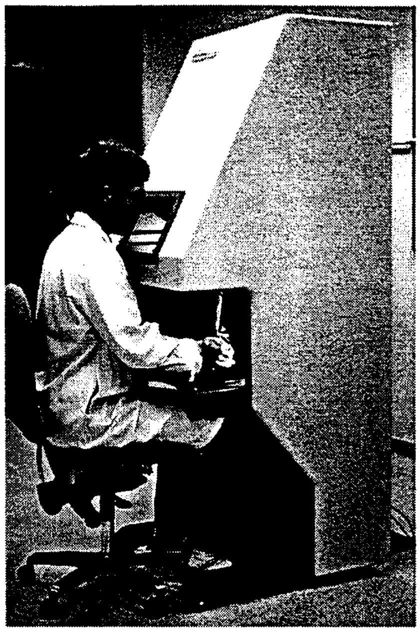
In this paper we discuss our ongoing development of the MEDFAST system, focusing on the TSW man-machine interface and its associated servo control electronics.

BACKGROUND

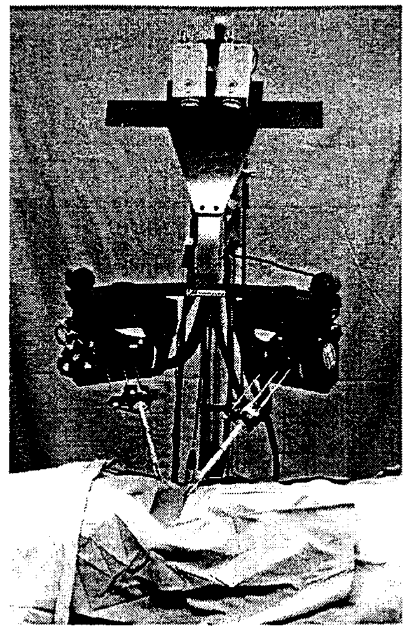
SRI International has previously developed and demonstrated a prototype telepresence surgery system [Green et al., 1995] that has been used to perform successful remote surgical procedures on animals. Other robotic and telerobotic systems have been developed for surgical applications [Burckhardt et al., 1995; Taylor et al., 1994], but only the SRI system provides the combination of responsive, force-reflecting telemanipulators and integrated visual feedback that allows surgeons to remotely perform the full spectrum of surgical maneuvers—for example, cutting, suturing, dissecting—with a high degree of dexterity and effectiveness comparable to their hands-on skills.

The SRI telepresence technology is an entirely new method of remote manipulation, with important potential applications in remote surgery and MIS. Surgeons who have worked with SRI's telepresence surgery demonstration system, with its fully integrated combination of three-dimensional (3D) video imaging, precise remote manipulation with handheld surgical instruments, and force feedback, agree that it is so compellingly realistic as to immediately dispel any sense of remote operation. Using the demonstration system, these surgeons have successfully performed three series of remote surgical procedures on pigs [Bowersox et al., 1996]. These first-ever remote surgeries included treatment of a variety of simulated abdominal and vascular injuries, including cholecystectomy, nephrectomy, repair of gastrotomy and enterotomy, and repair of femoral artery, liver, and bladder lacerations.

Shown in Figure 1, the demonstration system consists of two modules: a work-site module, where the actual object manipulation takes place, and an operator module that contains a strikingly realistic, 3D, video reproduction of the actual work space (not a computer model). This demonstration system incorporates many advanced technologies, including a highly responsive, force-reflecting master/slave manipulator with 4 degrees of freedom (DOF), stereoscopic video, and stereophonic sound. In effect, the operator grasps surgical instruments, reaches into what appears to be the actual workspace, and carries out complex tasks with quick, sure motions. Operating surgeons feel as though they are performing tasks right before their own eyes. The 3D image is created by a stereographic video system, viewed with a mirror. The surgeon looks downward, "through" the mirror, to see the surgical site below it, just where he or she is reaching



(a) The telepresence surgeon's workstation of the demonstration system provides two hand-control masters with surgical instrument handles, a stereographic view of the surgical field, and a microphone and speakers for communicating with the assistant at the remote site.



(b) The demonstration system remote surgery unit comprises two slave manipulators with interchangeable surgical instruments, a pair of stereographic video cameras, and stereo microphones.

Figure 1. Demonstration telepresence surgery system

with the hand controls. The control is a surgical-instrument handle mounted on a light, well-balanced, force-reflecting servo manipulator—the *master*. An identical *slave* servo manipulator at the operating table controls the actual surgical instrument—scalpel, forceps, and so forth—the tip of which is seen in the image, as if it were actually attached to the handle. When the tip touches the tissue, the resistance is felt from the handle. The overall effect is very compelling. With support from the National Institutes of Health, ARPA, and other sources, SRI has continued the development of this technology for remote surgery as well as laparoscopic and microsurgery applications.

THE ADVANCED SURGERY SYSTEM

System Block Diagram

- A simplified block diagram of the advanced system is shown in Figure 2. We have established specifications for the master and slave telemanipulators and the stereo video display. These specifications, which form the basis for the TSW design, are summarized below.

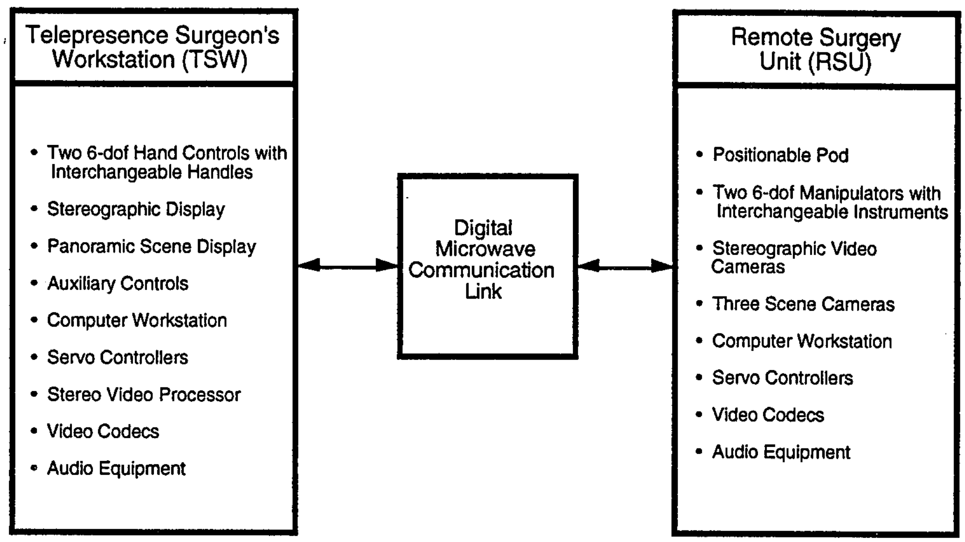


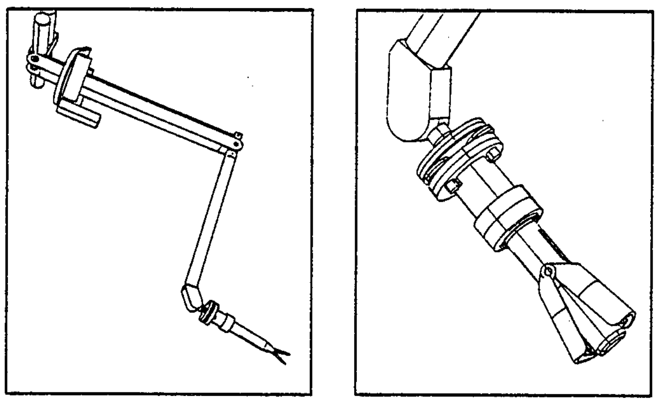
Figure 2. MEDFAST system block diagram. The MEDFAST system consists of the telepresence surgeon's workstation (TSW), the communication link, the remote surgery unit (RSU), and electronics modules associated with the TSW and RSU.

- Control handles for master manipulators, interchangeable for surgeon's use with either right or left hand
  - Hemostat handle
  - Forceps (pickup) handle
- Stereo vision system
  - Display resolution: 640 x 480 pixels, minimum
  - Camera resolution: 700 horizontal by 494 vertical lines
  - Stereo display type: 120 Hz full-frame with active or passive glasses

The New TSW

Based on the above specifications, we are developing a new TSW with two 6-DOF (plus grip) hand controls, enhanced displays, auxiliary controls, and all-new, ruggedized electronics. Using wood and metal mock-ups, we have had consulting surgeons perform simulated procedures, including suturing organ models, to evaluate the range of motions required for surgical procedures and guide our designs as they evolve. The surgeons are experienced in trauma, general, and vascular surgery, as well as other surgical specialties.

Master Manipulator Design: The proposed manipulator design is shown in Figure 3.



(a) Overview of manipulator

(b) Detail of master with pickup handle

Figure 3. Design of surgical manipulators

TSW Console Human Factors: The new surgeon's console has been designed to accommodate surgeons with a wide range of physical statures. The design will comfortably seat men and women ranging from the 5th to the 95th percentile in height, and will enable effective telepresence for all of them. Figure 4, based on data from Woodson and Conover [1964], illustrates the latitude of adjustment necessary. Our plan is to have the surgeon sit on a chair of adjustable height, which will bring his or her eyes to the proper location to view the display. A foot rest with foot controls will be brought up to match a comfortable foot height, and (if necessary) the master arms can be adjusted up or down to a comfortable position.

To accommodate the 6-DOF manipulators, the new surgeon's console will need to provide a much larger workspace than is afforded by the current console. Accordingly, the new console is designed to allow unimpeded motion of the control handles throughout a range of at least 1 cubic foot directly in front of the surgeon, to allow rapid and effective surgical treatment of trauma. The conceptual design is shown in Figures 5a, 5b, and 5c. For finer, more controlled procedures, such as suturing and micro dissecting, the console will include positionable forearm rests for stabilization.

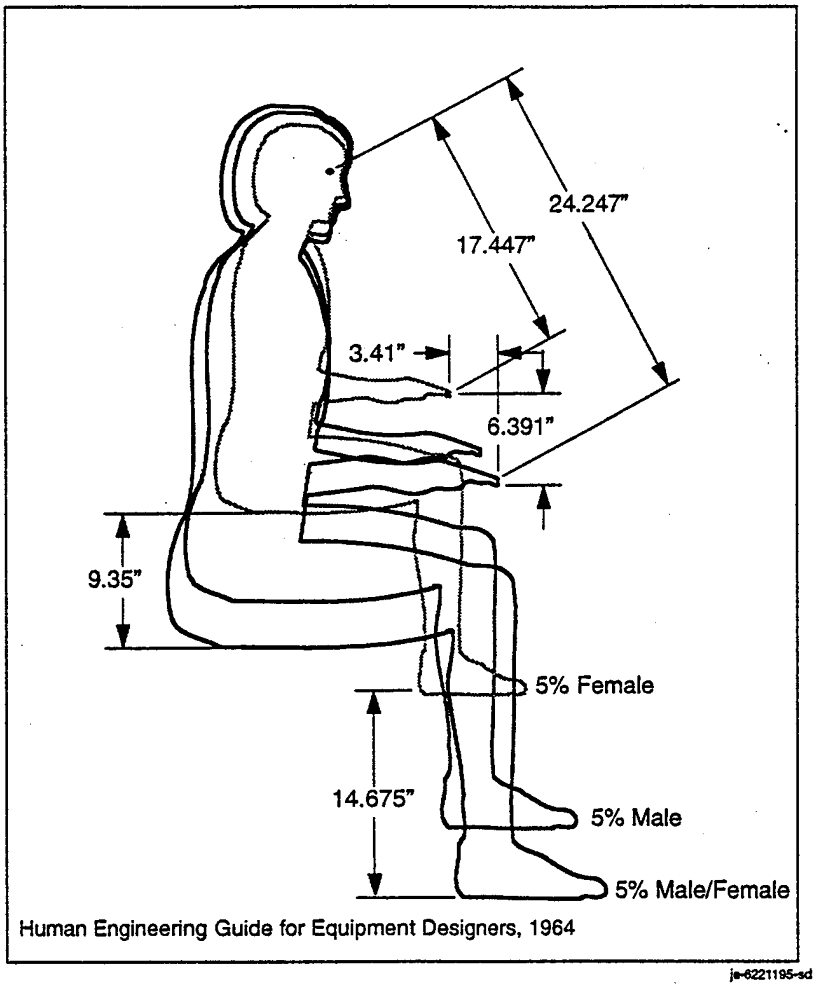
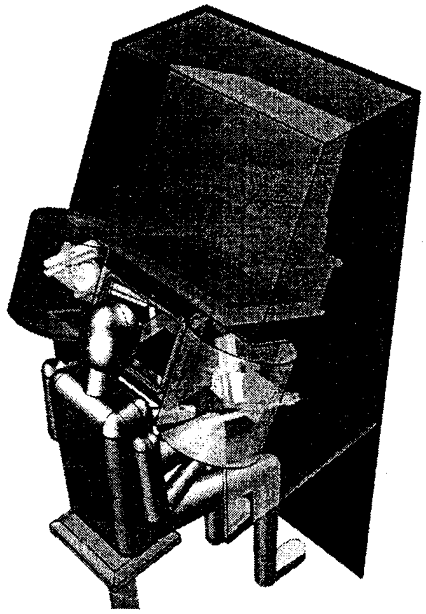
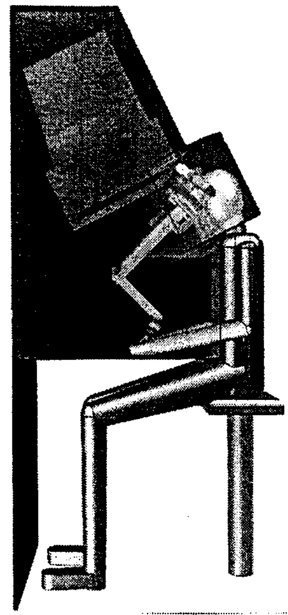


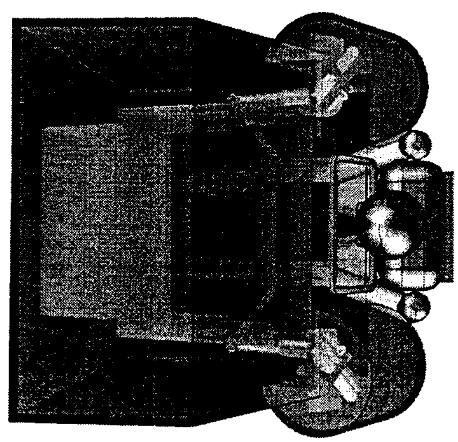
Figure 4. Variation in human dimensions



(a) Perspective view



(b) Side view



(c) Top view

Figure 5. Design of telepresence surgeon's workstation

Both the stereographic display and heads-up display are also included in the surgeon's workstation. The stereo display is viewed through a mirror as in our initial telepresence demonstration system. The heads-up display (not shown in Figure 5) will be at the back of the TSW console. Additional items not shown include foot controls, audio microphone, and stereo speakers.

Servo Controller

New servo electronics and algorithms have been developed to control the 6-DOF master and slave manipulators. To enable enhanced tactile feedback, enhanced dynamic response, and greater manipulator output force, we have developed and tested new control algorithms that employ a combination of force and position feedback. The algorithms have been tested using simulation and actual operation on a single-axis test stand.

Simulation: We have developed a model of our DSP-based controller and a motor-driven test axis using Matlab and SIMULINK (products of Math Works, Inc.) to aid in developing and testing different bilateral servo algorithms. We constructed a detailed analytical and numerical model of our control hardware and the dynamics of the servo control test stand so as to better understand the control issues and to speed and facilitate alternative control designs. The model includes discrete sampling effects and real-time computation delay effects.

Servo Test Stand: We have built a single-axis servo test stand to verify the simulation results. The test stand consists of two motor-driven axes with gearing and inertia similar to the elbow axis of the new manipulators. Each axis has a tachometer and potentiometer for determining step and frequency response. In addition, an external drive motor on one axis produces sinusoidal input (simulating operator hand motion) at different frequencies for determining transfer functions. A force sensor on the tip of each arm, sensitive to ±2 lb, is interfaced to the analog inputs of our servo controller.

Evaluation of Control Laws: We have evaluated the following known control laws for bilateral, force-reflecting control of teleoperated manipulators.

- **Position/position control**: First introduced over thirty years ago [Burnett, 1957], position/position control used bilateral position tracking to introduce some force reflection into a teleoperated manipulator.

- **Power steering and position/position control**: Local power steering can be introduced into the position/position control scheme by feeding back a force measurement to the local controller.

- **Position/position control and cross-coupled force reflection**: Power steering is made symmetric by passing force measurements between master and slave.

- **Position forward/force back:** This is an asymmetric control objective that has the slave manipulator follow the master manipulator's position only, while the master manipulator follows the slave's force measurement only [Flateau, 1969]. Additional damping is provided by some velocity feedback. This approach can an be used with a single (slave) force sensor.

- **Ideal kinesthetic coupling**: A physically derived control law using acceleration feed forward and cross-coupled force measurements provides "ideal kinesthetic coupling" [Yokokohji and Yoshikawa, 1994].

We are currently evaluating each of the control laws listed in Table 1 with computer models and the single-axis servo test stand.

Table 1

KINESTHETIC COUPLING CONTROL LAWS

	Performance	Passive	Optimality and Tuning
Bilateral position tracking (BPT)	Tracks position, force tracking contaminated by manipulator inertia	Yes	No automatic tuning, suboptimal performance
Power steering with BPT	Reduced inertia compared to BPT alone, loss of contact stiffness	No	No automatic tuning, suboptimal performance
Bilateral force amplification with BPT	Good stiffness and low inertia	No	No automatic tuning, suboptimal performance
Position forward/ force back	Good stiffness and low inertia, can be used with single force sensor	No	No automatic tuning, suboptimal performance
Ideal kinesthetic coupling	Good stiffness and low inertia	Yes	Model-based tuning, suboptimal performance (acceleration filtering)

New Control Electronics: New control electronics have been designed and built to accommodate both force- and position-feedback signals.

COMMENTS AND CONCLUSIONS

As part of SRI's ongoing project to develop a MEDFAST telesurgery system for ARPA, we are developing an advanced TSW design that will enable highly effective telepresence for remote surgery as well as MIS applications, and will also serve as an excellent immersive interface for surgical training using computer-based anatomical models. The TSW will include 6-DOF (plus grip) force-reflecting master manipulators, high-resolution 3D video, heads-up peripheral video displays, foot switches, and other I/O devices. The new console will allow unimpeded motion of the master control handles throughout a range of at least 1 cubic foot directly in front of the surgeon, enabling rapid and effective surgical treatment

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